Interdisciplinary Teamwork Challenges in a Design Competition Team

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Introduction

Communication and collaboration are key components of engineering work (Trevelyan, 2014), and teamwork, including interdisciplinary teamwork, is increasingly seen as an important component of engineering education programs (Borrego, Karlin, McNair, & Beddoes, 2013; Male, Bush, & Chapman, 2010, 2011; Paretti, Cross, & Matusovich, 2014; Purzer, 2011). Employers and education researchers alike advocate teamwork as a means of developing skills that engineering graduates need (Purzer, 2011), and accreditation bodies consider the ability to both lead and function on teams as an important outcome for engineering graduates (Engineers Australia, 2017). However, "despite the clear emphasis on teamwork in engineering and the increasing use of student team projects, our understanding of how best to cultivate and assess these learning outcomes in engineering students is sorely underdeveloped (McGourty et al., 2002; Shuman, Besterfield-Sacre, & McGourty, 2005)" (Borrego et al., 2013, p. 473). In order to contribute to the current conversation on interdisciplinary teamwork in engineering education, and to advance understandings of how best to cultivate teamwork learning outcomes, this paper discusses the most common teamwork challenges and presents *boundary negotiating artifacts* as a conceptual framework for addressing them. Drawing on data from long-term ethnographic observations of a design competition project, and the challenges students experienced, we utilise findings from a systematic literature review and the conceptual framework of *boundary negotiating artifacts* to present a case study of how boundary negotiating artifacts can support important teamwork constructs.

Background

Boundary Negotiating Artifacts

Boundary negotiating artifacts (BNAs) are "artifacts and surrounding practices to iteratively coordinate perspectives and to bring disparate communities of practice into alignment, often temporarily, to solve specific design problems that are part of a larger design project" (Lee, 2007, p. 318). BNAs are important to multidisciplinary teamwork because they can help establish the shared understandings that are necessary to successfully complete a project. In the original typology, five types of BNAs were identified (Lee, 2007). BNAs can take the form of sketches, prototypes, tables, concept maps, models and narratives, among many other forms. For a more in-depth review of boundary negotiating artifacts, see Beddoes, Borrego, & Jesiek (2011) and Beddoes & Nicewonger (2019).

Teamwork Constructs

A prior systematic literature review identified five leading constructs salient for engineering education teamwork (Borrego, Karlin, McNair & Beddoes, 2013). The constructs were: 1) social loafing, 2) interdependence, 3) conflict, 4) trust, and 5) shared mental models. As summarised in Table 1, this paper will focus on constructs 2-5, because we have observed that social loafing is less relevant for real-world competition projects, such as the one observed in this project, and postgraduate teams. Additionally, unlike the other constructs, social loafing is not related to interdisciplinary communication in the same way the other constructs are. We focus here on those constructs that can be supported by BNAs. Shared mental models are discussed in greater detail as they may be less well understood than the first three constructs.

Table 1: Leading Teamwork Constructs from Prior Literature*

Construct	Definition
Interdependence	Level of reliance on others in order to complete one's work
Conflict	Perceived incompatibilities or discrepant views among team members
Trust	Confidence in others; faith in trustworthy intentions of others
Shared mental models	Shared knowledge structures that enable a team to form accurate explanations and expectations, coordinate actions, and adapt behaviours

*Adapted from Borrego, Karlin, McNair & Beddoes, 2013. p. 488

Shared mental models (SMM) - also sometimes referred to as *team mental models* – are, most simply, knowledge structures that are shared by members of a team. SMMs include shared knowledge about the team's job or task, team member interactions, and team composition (Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000). More specifically, components of TMMs include (but are not limited to) correct understanding of: team members' knowledge, skills and attitudes; team members' roles, responsibilities, role interdependencies; and the team's information sources, communication channels, task procedures, and task component relationships (Mathieu et al., 2000). Having such shared knowledge, enables a team to plan, coordinate their actions, form accurate expectations and explanations of the task and of team members' behaviours, and to adapt their behaviours accordingly - all of which leads to better team performance (Cannon-Bowers, Salas, & Converse, 1993; Edwards, Day, Arthur, & Bell, 2006; Langan-Fox , Anglim, & Wilson, 2004; Kozlowski & Ilgen, 2006; Mathieu et al., 2000; Mathieu, Heffner, Goodwin, Cannon-Bowers, & Salas, 2005).

More specifically, Cannon-Bowers, Salas, & Converse (1993) proposed that a team is most likely to be effective if team members share four mental models. The *equipment model* captures team members' shared understanding of the technology and equipment with which they carry out their team tasks. The *task model* captures team members' perceptions and understanding of team procedures, strategies, task contingencies, and environmental conditions. The *team interaction model* reflects team members' understanding of team members' responsibilities, norms, and interaction patterns. And the *team model* summarises team members' understanding of each other's knowledge, skills, attitudes, strengths, and weaknesses.

The goal of this paper is to show that BNAs can be an important pedagogical tool in helping students develop a shared mental model and should be proactively utilised to do so. BNAs can also be strategically employed to promote effective interdependence and trust and to minimise conflict. Examples of previously-identified pedagogical strategies for promoting interdependence and trust and minimising conflict can be found in Borrego, Karlin, McNair, & Beddoes (2013). As reported in that article, interdependence can be promoted through complex projects, group processing, and group grading. Trust can be promoted through teambuilding activities and minimizing monitoring behaviours. Conflict can be minimised through having clear goals and values, allowing time and activities for consensus-building, and training on how to deal with conflict. However, the relationships between BNAs and these teamwork constructs has not yet been widely examined.

Setting and Methods

The ethnographic research informing this paper came from twelve months of fieldwork among students and faculty at a large research university in the United States. The interdisciplinary design project studied was part of an international collegiate competition. The competition promoted green living and sustainable design the through creation of tiny homes. The design team was made up of multiple sub-teams. We use the term "sub-team" to reflect the aggregated way in which varying aspects of this design project were assigned to different groups of students and faculty. While there were multiple sub-teams working on this project, the observations informing this paper are from the architecture sub-team and the mechanical engineering sub-team. Student participation differed from sub-team to sub-team; some were paid to manage and work on the project, some were volunteers, and some were enrolled by virtue of being in a course that utilised the project as assignments for the course. The latter was the case for the engineering sub-team who participated in the project as part of their capstone design course.

The primary method of data collection involved participant-observation of student and instructor interactions. These interactions occurred during group meetings and in studio-classroom settings. Sixteen individual, semi-structured interviews were also conducted with students. In the interviews, students were asked to reflect on their experiences working with the other students on their sub-team; their experiences working with members of other sub-teams; and their understanding of the central objectives of the design project. Additional, questions asked students to describe how the project they were working on related to their professional development and how their understanding of the project shifted over the course of their time working on it. The data informing this paper were identified by the authors by comparatively reviewing the fieldnotes, interview data, and reflecting on the experiences that they had with the participants in this study. Participant names used are pseudonyms.

Ethnographic research is designed to produce rich, deep understandings about one particular group or context (Case & Light, 2011). It is not designed to produce findings that are necessarily representative of all groups or contexts. Therefore, these findings do not vie to represent all interdisciplinary student team projects. Rather, readers themselves can determine applicability and utility of this analysis for their context.

Findings & Discussion

The engineering students were introduced to the design project through a project narrative at a joint meeting facilitated by the project's team leaders. This presentation was accompanied by richly illustrated images of the design site, including renderings of both the tiny-home's interior and exterior layouts. In presenting the aims of the project, the team leaders encouraged the engineering students to be innovative, and they asked them to look for ways to further expand on the project's design. The engineering students left the meeting excited to be a part of the project. However, over the course of the semester, their enthusiasm began to waver. By the end of the semester, their project took a radical turn, which required them to abandon their initial goal of designing an innovative, natural ventilation system, resulting in high levels of dissatisfaction among the engineering students. The prototypes that were created by the engineering sub-team were never incorporated into the project's overall design, since they were unable to align their work with the continual changes that were being made to the project by the other sub-teams. Many of these changes came about unexpectedly, which in turn made several of the assignments that the engineering students worked on ultimately not applicable or feasible.

The following paraphrased exchange in which the engineering professor and students reflect on their experiences took place at the end of the capstone course. It began with the professor asking the students to tell the rest of the class about their experiences working with the architects because, he said, "there are lessons there."

Eric:	This is an on-going project and we had only interface with a small portion of it. The biggest issue we had was with all the

	different teams. There's the [name of sub-teams] and the in-house people. With so many people we would go one direction and then they would change; someone high up would want something different.
Saul:	Also, collaboration with all those teams did not happen until after mid-way in the semester. Before then the focus was on the theory of natural ventilation. But then we had a serendipitous meeting, we asked them about what our deliverable was and they started arguing with one another. They didn't give us a clear project until 7 weeks into the semester.
Professor Smith:	You had a hierarchy of groups. Did they listen to you when they talked to you?
Eric:	We had difficulty communicating with the different groups.
Professor Smith:	You were told what your solution was.
Saul:	Yeah, they didn't give us a problem to solve. They gave us an arbitrary thing to figure out how to make: design a system that opens and closes.
Professor Smith:	In fact, it was a micro-solution and the other teams you were working with were constrained by the cost. It's not that natural ventilation is a bad idea, but they didn't couch it in any type of larger goal. In the end, you were to build something for them. Build a window with a motor. The design process was constrained; there is very little potential for exploration and the development of a solution.
Ty:	It wasn't just the cost, it was the fact that the ventilation system they wanted us to design uses lots of energy and it really only saves lots of energy when there is a huge differential. Like when you have a weird situation where the home is really hot and outside it's really cold.
Professor Smith:	You felt at the end frustrated, stressed, and your ownership is modest. Appropriate agency matters on how these things work out. You needed to have more agency over all of this.

This one meeting captured a series of challenges the engineering students experienced over the course of the project. Each of the four teamwork constructs identified in the Background were evidenced in the conversation. Interdependence was present, but in an uneven, ineffective manner. That is, the engineering students' work was highly interdependent with the architecture students' work, but the architecture students operated largely independently of the engineering students. Rather than facilitating interdisciplinary learning, the uneven, ineffective interdependence was a source of conflict for the engineering students.

The team did not have a Shared Mental Model (SMM) for many aspects of the project. This was a challenge for the engineering students as they did not share important knowledge that they needed to accomplish their work. For instance, they lacked a SMM of task procedures, task strategies, task component relationships, roles and responsibilities, and communication channels, among others. These types of shared knowledge have been shown to contribute to successful teamwork (Beddoes & Borrego, 2014; Cannon-Bowers et al. 1993; Edwards et al., 2006; Kozlowski & Ilgen, 2006; Langan-Fox et al., 2004; Mohammed et al., 2010). Furthermore, lacking effective communication and a shared mental model, it was difficult to develop trust among the sub-teams.

The lack of a shared mental model and trust, combined with the uneven interdependence, led to conflict. Conflict was evident the engineering students' dissatisfaction, lack of agency and lack of useful learning outcomes. The engineering students left the project feeling very dissatisfied with the experience and their interactions with the other disciplines. Much of the conflict stemmed from a lack of effective communication.

Each of these challenges could have been minimised by more strategic use of boundary negotiating artifacts, as summarised in Table 2. Conflict would have been mitigated and trust promoted had more attention been paid to the creation of a shared mental model. More effective use of BNAs could have helped in this regard. For instance, had proposing artifacts been better used to communicate changes in direction, the engineering students would have had more components of a shared mental model and consequently a better understanding of the task at hand. Had aligning artifacts been better used to coordinate and produce shared understanding of a design problem that was interesting to all involved, they might have ended up with a more meaningful capstone design project.

A structuring artifact in the form of a project narrative was used to articulate a vision for the project, but it was not sufficient on its own to create a SMM. It was created by the architects, and while it was useful to them, their over-reliance on the narrative alone when communicating with other sub-teams contributed to the lack of a SMM.

This is not to say that a lack of BNAs was the only problem; certainly, there were organizational and structural issues, such as the fact that the engineering students were participating as part of a required course, that added to the challenges.

Table 2: Modified Boundary Negotiating Artifacts typology

Type*	**Purpose****	**Construct-related Affordances**
Proposing	Propose new ideas, concepts, or forms to team members: a reference or symbol for a new idea	• Promote SMM • Reduce conflict
Aligning	Create alignment and coordination between the team members to bring them together long enough to produce a shared understanding of a problem and/or to communicate important information	• Promote trust • Promote SMM • Reduce conflict
Structuring	Communicate a vision and compete with other structuring artifacts to make that vision dominant: push and negotiate boundaries between communities: establish ordering principles: direct and coordinate the activity of others	• Promote SMM • Promote effective interdependence • Reduce conflict

*Modified from Lee, 2007
**Lee, 2007

In Table 2, the names of two BNAs were modified in the interest of clarity based on prior experiences presenting the concept. *Inclusion* artifacts were changed to *proposing*, and *compilation* artifacts were changed to *aligning*.

Conclusion

During a year-long participant observation with a design competition project involving engineering, computer science and architecture students, among others, we observed the leading engineering education teamwork constructs (interdependence, conflict, trust, SMM) in action. Through observing the challenges they encountered, we can conclude that in interdisciplinary project teams, boundary negotiating artifacts provide a conceptual framework and pedagogical tool for promoting desired teamwork outcomes and minimising undesired outcomes. BNAs can be proactively utilised by instructors and students to avoid conflict and promote shared mental models, trust and effective interdependence. These findings echo those of another similar study (Beddoes & Borrego, 2014), and provide further evidence of the importance of shared mental models in particular.

Student teams cannot simply be thrown together and effective learning and teamwork expected to happen automatically; such skills must be proactively developed (Beddoes & Borrego, 2014). Naming and discussing these constructs and types of BNAs as a pre-teamwork intervention could help students identify, navigate, and avoid challenges that hinder successful interdisciplinary teamwork. Specifically, introducing them to the concepts by identifying the different components of a shared mental model and the three types of BNAs in Table 2, explaining why they matter, and creating activities and materials to help students establish those components of a SMM would be useful. This requires time dedicated at the start of the course, as well was throughout, to creating shared understandings and goals though group processing and creation of BNAs.

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